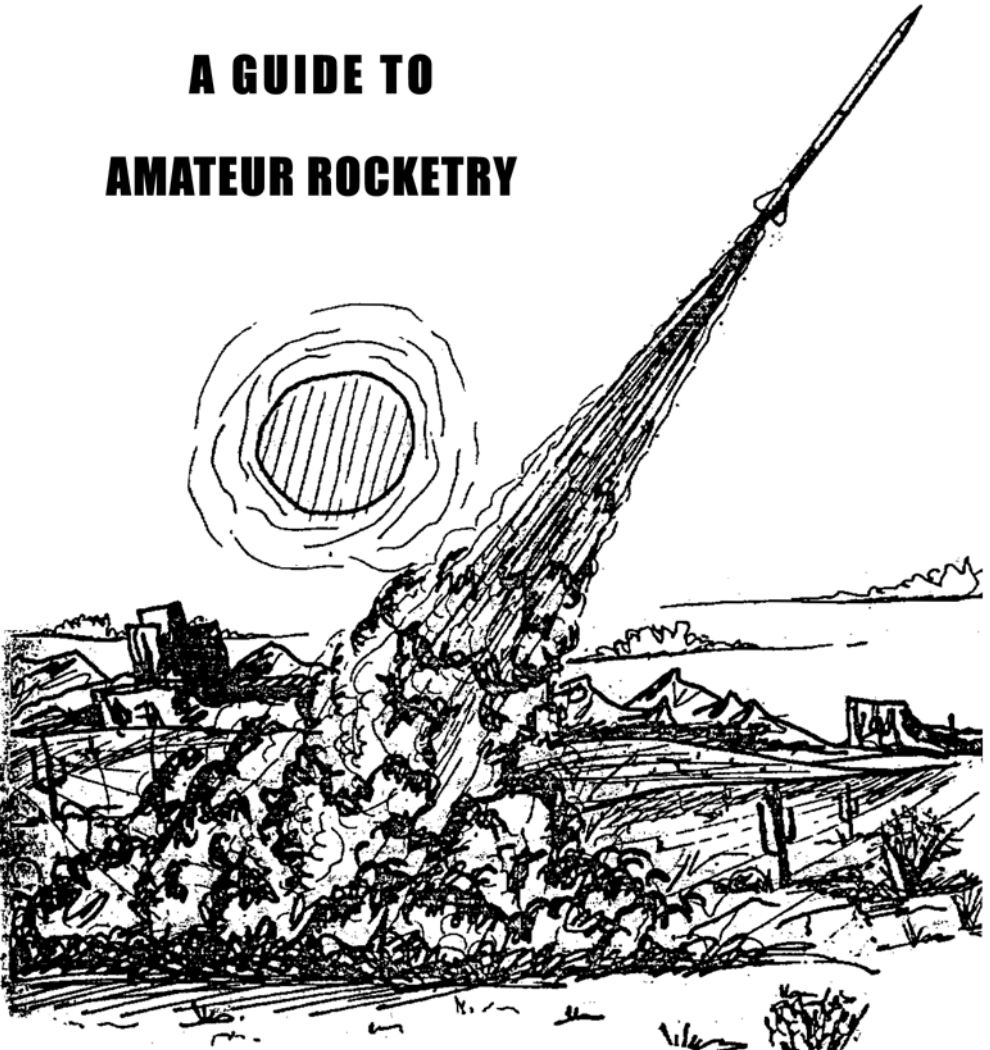
Downloaded from http://www.everyspec.com

A GUIDE TO AMATEUR ROCKETRY



U.S. ARMY
FIELD ARTILLERY SCHOOL
Fort Sill, Oklahoma

Downloaded from http://www.everyspec.com

MAJOR GENERAL CHARLES P. BROWN

Commanding General, U. S. Army Field Artillery Center and Fort Sill

Commandant, U. S. Army Field Artillery School

Downloaded from http://www.everyspec.com

PREFACE

The tremendous interest in rocket development by high school and college students has been the source of much gratification to those who are most interested in the future of rockets and guided missiles. We foresee great benefit to our Nation as a consequence of this scientific curiosity on the part of the generation which will soon bear the responsibility for our scientific progress. The United States Army desires to extend the maximum degree of assistance to, and to cooperate fully with, these budding scientists in their experimentations.

We recognize that there is an ever-present danger in the use of experimental rockets. Our newspapers record altogether too many instances in which young students have been seriously injured in the use of these devices. In the interest of increased safety, the United States Army Field Artillery Center at Fort Sill, Oklahoma, has made range facilities available to young scientists of the surrounding vicinity to permit the firing of experimental rockets with a high degree of safety.

To further assist our young scientists, the United States Army Field Artillery School has prepared this booklet. Much technical data on military rockets and the high-impulse propellants which are used in such weapons is available in the Army; unfortunately, little technical data is available on the low-impulse propellants which are considered most suitable for experimentation by students. Accordingly, through a program of experimentation and research, the information contained in this booklet has been collected. Other sources may be more detailed and may develop this subject to a higher degree in certain respects. However, we believe that this booklet will be of assistance to those high school and college students who are beginning their experimentation in the development of rockets.

Inquiries regarding the use of military range facilities and comments and questions regarding this booklet should be addressed to:

Commandant
U. S. Army Field Artillery School
ATTN: AKPSIAS-GM
Fort Sill, Oklahoma 73503

Charles P. Brown

CHARLES P. BROWN
Major General, USA
Commanding

Downloaded from http://www.everyspec.com

FOREWORD

Empirical information contained in this booklet is based on data obtained from 36 actual firings and 6 static firings of zinc-sulfur propelled rockets. Flight performance was measured by radar and slow motion photography. Thrust, chamber pressure, and burning time were monitored during the static firings. The six static firings constitute a limited sample. Comparison of burning rates obtained from slow motion photography in actual firings and those obtained during static firings are not wholly in agreement. For this reason, burning rates used in the examples contained herein are not conclusive.

Values included in the examples and the preparation of the tables are based on slide rule computations.

Reproduction is authorized provided proper credit is given to the U. S. Army Field Artillery School, Fort Sill, Oklahoma.

Downloaded from http://www.everyspec.com

CONTENTS

		Page
CHAPTER 1.	Introduction	4
2.	Propellants and the combustion process	8
3.	Rocket engine design	13
4.	Ignition systems	26
5.	Aerodynamic surfaces	29
6.	Rocket launchers	33
7.	Rocket testing and performance analysis	37
8.	Organization	44
9.	Safety	46
GLOSSARY		49

Downloaded from http://www.everyspec.com

CHAPTER 1

INTRODUCTION

1. GENERAL

One of the most fascinating modern hobbies is designing and constructing solid-propellant rockets. This booklet has been prepared to help young people who are interested in this hobby. The material in this booklet is elementary to rocket science. More detailed and specific information is available in books written by professional rocket designers. Many news items have been written about the success achieved by young people in firing their home-constructed rockets. Perhaps, also, you have read about some of the unfortunate accidents which have resulted in death or injury to young rocketeers. This booklet discusses some of the basic principles and practices that help to make rocketry safer.

2. COMPONENTS

Rockets can be as complicated as the Saturn V booster or as simple as a Fourth of July skyrocket. Most rockets consist of at least four parts (fig 1): an engine, where the thrust, or push, is created; a nose cone, which helps divide the flow of air around the rocket; a body section, which holds the other parts together; and the tail fins, which give the rocket stability just as feathers on the end of an arrow provide stability. Some rockets contain equipment to help guide the rocket as desired. In the Army, this type of rocket is called a guided missile; for example, the Pershing and Sergeant guided missiles, which may be seen at Fort Sill, Oklahoma. Before concentrating on the design of rockets, let us review some of the basic principles of rocketry.

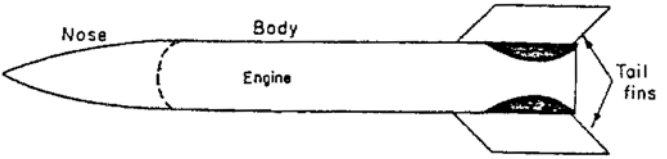


Figure 1. Parts of a rocket.

3. PROPULSION

The thrust, or propulsive force, created by a chemical rocket engine is the result of the combustion of a fuel and an oxidizer. There are several types of chemical rockets, the most important of which are solid-propellant and liquid-propellant rockets. Each of these types has its own advantages and disadvantages. This booklet deals exclusively with solid-propellant rockets; their relative simplicity and economy and their relative ease and safety of handling, loading, and firing make them more suited to amateur rocketry applications than liquid-propellant rockets.

Downloaded from http://www.everyspec.com

A typical solid-propellant rocket engine is shown in figure 2. The solid propellant may be compacted to form a solid grain or it may be loose. The propellant is completely enclosed by the combustion chamber except for the end of the chamber where the nozzle is attached. A blow-out

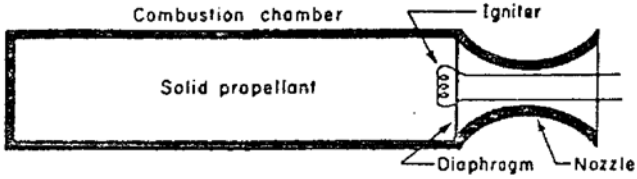


Figure 2. Typical rocket engine.

diaphragm is used to retain the propellant in the chamber during loading, storage, and movement and to help build up pressure during ignition. The propellant is ignited by a wire which is heated by electric current. The nozzle assists in converting the energy of heat and pressure created in the combustion chamber to energy of motion. The resulting thrust, or forward force, is approximately equal to the exhaust velocity times the weight of the propellant burned each second divided by the gravitational constant. First, consider a chemical reaction which produces heat or fire. A fire can be created only if three elements are present: a fuel, such as wood, gasoline, or alcohol; an oxidizing agent, such as the atmosphere, liquid oxygen, or another chemical that contains oxygen or reacts similarly to oxygen; and an ignition system to kindle, or light, the fire. But how is a fire used in a rocket engine to produce thrust? Since the fire is confined on all sides but one, the chemical reaction is concentrated so that it builds up pressure and heat. Through proper design of the engine, which we will consider later, the energy of heat and pressure is converted to energy of motion. The rapid movement of the burning gases from the engine chamber creates the thrust. Chemicals which burn rapidly produce more thrust in a given period of time than chemicals which burn slowly, but the more rapid-burning chemicals are generally the more dangerous. To be practical, and to live to enjoy the hobby of rocketry, you must settle for chemicals which do not react violently. From this short discussion on the use of fire to create thrust, many factors become apparent. The engine must be able to withstand the tremendous heat and pressure created. An ignition system is required, and for safety reasons the ignition system must be remotely operated. Remote operation may be easily accomplished by using a battery and several hundred feet of wire. The chemicals to be used in the rocket must contain a fuel and an oxidizer. If you are interested in making a model plane which is rocket propelled, the best idea is to buy a small rocket unit from your local hobby shop. These small rocket units produce enough thrust to maintain a model plane in flight and are very inexpensive. For any young rocketeer, it is advisable to buy one of the commercial units just to become accustomed to working with rockets and to get an idea of how a rocket operates. The rocket may be attached to a small toy racing car or to a rocket ship,

Downloaded from http://www.everyspec.com

which may be suspended on hooks and hung on a clothesline wire. Small cartridges of carbon dioxide are also available. These units produce thrust when a soft metal seal at one end is punctured. The advantage of the carbon dioxide unit is that there is no fire hazard. The unit does, however, become extremely cold during operation; so be careful when you handle the cartridge.

4. AERODYNAMIC PROBLEMS

The next factor which influences the operation of a rocket is called aerodynamics, the science dealing with the forces that act on objects moving through the air. An airplane obtains lift, or an upward force, by the relative motion of air above and below the wings. The air passing around the wings creates an upward force, the engine drives the plane forward, and the wings keep the plane aloft. In designing a rocket, you must decide whether you want the rocket to travel a path similar to that of an airplane or to travel a curved path like that of a bullet or baseball. The path traveled by an airplane is called a supported trajectory; that is, the airplane is supported by wings. The path traveled by a bullet or baseball is called a ballistic trajectory. If you decide to make a ballistic-type rocket, the aerodynamics problem will be greatly simplified, since there will be no large lifting wings--just a set of three or four tail fins. The purpose of the fins is to provide stability. They help reduce the tendency of the rocket to wobble or go end over end. As the rocket passes through the air, the fins tend to straighten out the flight of the rocket. If the rocket were to turn slightly, the air would create a pressure difference on the fin surfaces and the force of this pressure would push the rocket back into line. To determine whether or not your rocket will be stable, find the center of gravity, or balance point, at which all weight seems to be concentrated (fig 4). Be sure to do this both before and after you load propellants in the rocket. Then examine the tail surfaces to see if the approximate geometric center of all the tail surfaces is to the rear of the center of gravity with the rocket both empty and loaded. The rocket will probably be stable if the center of pressure (center of all tail surfaces) is to the rear of the center of gravity.

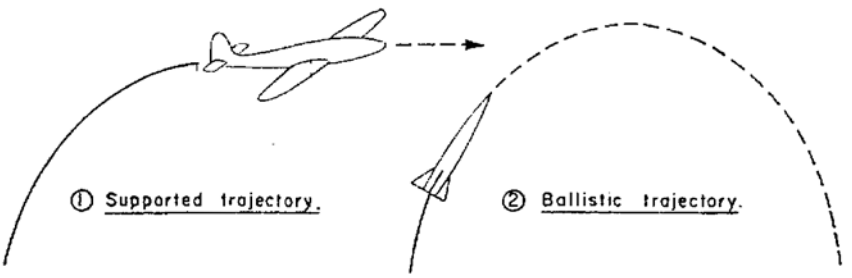


Figure 3. Trajectories.

Downloaded from http://www.everyspec.com

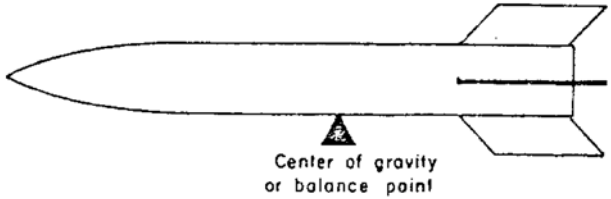


Figure 4. Center of gravity.

a. Alinement. Your rocket components, or body sections, must be very carefully alined. The direction of thrust must be exactly along the centerline of the rocket (through the center of gravity) and parallel to the desired direction of motion, and all of the fins must be perfectly alined with the rocket body. If not perfectly alined, the rocket will turn in an unknown direction and may even turn fast enough to break up or dive into the ground just after takeoff.

b. Forces. Two forces retard the flight of a rocket through the atmosphere. These are the drag, or resistance, created by the air and the downward attraction of gravity. That is, for your rocket to rise into the atmosphere, the thrust of the engine must exceed the weight of the entire rocket. The amount of drag increases with the speed at which the rocket travels. Other very important factors that affect drag include the cross-sectional area of the rocket as seen from the front, the amount of streamlining, and the atmospheric conditions.

c. Construction. Proper design of the rocket will minimize drag through streamlining and through keeping the cross-sectional area at a minimum consistent with propulsion requirements. The rocket should be as slim as possible without being weak enough to bend. The tail fins should be made of thin metal (perhaps 1/16-inch steel or 1/8-inch aluminum). Wood and paper tail surfaces will not stand up under the high velocities and forces that normally occur during rocket operation. The bases of the fins should be bent 90° and can be fastened to the body or rocket engine. The nose section is normally in the shape of a cone with an internal angle of about 30°. The rocket can be made with a separate body and the other components mounted on the body. However, considerable weight can be eliminated if the nose cone and tail fins are mounted directly on the rocket engine; the rocket engine provides the structural strength as well as the combustion chamber. Both of these construction techniques will be discussed later.

Downloaded from http://www.everyspec.com

CHAPTER 2

PROPELLANTS AND THE COMBUSTION PROCESS

5. CHEMISTRY OF PROPULSION

The energy to propel the rocket is obtained from materials which are caused to burn or undergo a chemical reaction with the release of energy. A properly designed chamber and nozzle convert the maximum amount of the energy released during combustion to a form of mechanical energy called kinetic energy or energy of motion. A very simple heat producing chemical reaction is the combustion of hydrogen (H_2) and oxygen (O_2) to form water plus heat. The reaction is--

$$2\,H_2 + O_2 \longrightarrow 2\,H_2O + \text{heat}.$$

Likewise, the reaction between hundreds of other fuels and oxidizers releases heat. Another method of obtaining heat that is normally not thought of as combustion is the reaction between zinc (Zn) and sulfur (S) to form zinc sulfide:

$$Zn + S \longrightarrow ZnS + \text{heat}.$$

Other combinations of chemicals produce heat during reaction. Some chemical combinations require the addition of heat for continuous reaction and, of course, would not meet the requirements for propellants which must release energy to be usable in rockets.

6. PROPELLANT CHARACTERISTICS

The primary consideration for large military or scientific rockets is to obtain the maximum thrust for a minimum of weight. Although this is a general consideration for any rocket, high thrust is normally sacrificed in small experimental rockets to permit operation with propellants which are readily available at a low cost and are not too dangerous to handle. Some of the desired characteristics of experimental rocket propellants include the following:

a. Nontoxic. The propellant should not give off poisonous fumes and should not be poisonous to the skin, since it is necessary to handle the propellant to fill the rocket motor.

b. Not highly flammable. The propellant should not give off vapors which could be accidentally ignited several feet from the rocket. It is also desirable that the propellant not burn well under atmospheric pressure. This helps prevent burning someone if the rocket rises, explodes, and scatters chunks of burning propellant about.

Downloaded from http://www.everyspec.com

c. Not sensitive to shock. Normal handling of the propellant during transporting, filling the combustion chamber, or preparing the rocket for firing should not cause detonation by shock. Unfortunately, no known practical propellants have all the desirable characteristics; therefore, a compromise must be made between available energy and ease and safety in handling. For example, a zinc and sulfur mixture is relatively insensitive to shock but burns rapidly at atmospheric pressure when loosely packed and is easily ignited by a spark.

7. RELATIVE QUANTITIES OF EACH PROPELLANT

To determine the quantity of each of the chemicals to use for a particular combination, you must apply the laws of chemistry concerning balanced chemical equations. For example, assume that you want to find the relative amounts of pure zinc powder and sulfur required to produce a complete reaction. The chemical formula for zinc and sulfur to produce zinc sulfide is--

$$Zn + S \longrightarrow ZnS.$$

Now, determine the formula weights of the chemicals used. The formula weight equals the sum of the weights of the atoms indicated by the formula. The atomic weight of zinc is 65. 38; that of sulfur is 32. 07. One atom of zinc combines with one atom of sulfur.

Formula (or molecular) weight = (number of zinc atoms x atomic weight of zinc) + (number of sulfur atoms x atomic weight of sulfur);

Formula weight = (1 x 65. 38) + (1 x 32. 07) = 97. 45. This relation is true regardless of the weight-unit (pound, gram, kilogram) that is used.

Thus, formula weight = 65. 38 pounds of zinc + 32. 07 pounds of sulfur = 97. 45 pounds.

For 1 pound of propellant, divide the weight of each chemical by the formula weight.

$$\text{One pound of propellant} = \frac{65.38}{97.45} \text{ pounds of zinc} + \frac{32.07}{97.45} \text{ pounds of sulfur.}$$

One pound of propellant = 0. 67 pound of zinc + 0. 33 pound of sulfur.

For 8 pounds of propellant, multiply each part of the equation by 8.

8(0. 67 lb zinc) + 8(0. 33 lb sulfur) = 8 pounds of propellant.
5. 36 pounds of zinc + 2. 64 pounds of sulfur = 8 pounds of propellant.

Another way to express the relative amounts of each propellant is by ratio. Divide the larger weight by the smaller weight.

Downloaded from http://www.everyspec.com

$$65.38\ (Zn) + 32.07\ (S) = 97.45\ (ZnS)$$

$$\frac{65.38\ (Zn)}{32.07\ (S)} = \frac{2.04\ (Zn)}{1\ (S)}$$

Use 2.04 parts zinc to 1 part sulfur (by weight).

It is difficult to determine the relative amounts of the various chemicals in propellants containing many elements; however, a chemistry teacher could help you determine the amounts in complicated mixtures.

8. PROPELLANT PERFORMANCE DATA

The safest and usually the most efficient solid propellants are those made specifically for model rocket engines. Contact a local hobby shop for information on commercial propellants or write the manufacturers. To design a rocket engine, it is necessary to obtain data on burning rate, desired chamber pressure, effective exhaust velocity, burning temperature, and ratio of specific heats. With this information, the size and length of the nozzle and chamber can be computed, thus providing the maximum thrust without creating conditions which would rupture the engine. By simply packing propellant into a chamber not specifically designed for that propellant, there is danger of creating an explosive reaction or obtaining only a fraction of the available thrust. Ten pounds of propellant in a properly designed system may cause the rocket to go 20,000 feet high. With a poorly designed engine, the rocket may travel only a few hundred feet high. For best results from noncommercial propellants, study information on the previously discussed factors which affect thrust. Check the library for books written 20 to 30 years ago about experimental rockets. During that time, many different propellant combinations of simple compounds and elements were tried. The propellants designed today are extremely complex and are too difficult and dangerous to duplicate.

9. COMBUSTION PROCESS

The actual combustion of most propellants is extremely complex. However, enough is known to enable engineers to design workable systems. Ignition and initial combustion must usually be under pressure; so a closed chamber is required. A plastic insert or diaphragm can be placed in the nozzle. The ignition system creates heat which ignites the propellant. The resulting pressure buildup ruptures the insert. In the meantime, the pressure buildup should be sufficient to sustain continuous combustion. If the propellant is a solid grain, the flame progresses in a direction perpendicular to the surface. The rate at which the flame progresses is called burning rate. Knowledge of the burning rate at the particular chamber pressure expected is the most critical factor in the design of solid propellant rocket engines. Other factors can be approximated without affecting the computations more than 50 percent.

Downloaded from http://www.everyspec.com

However, burning rate errors could affect the thrust as much as 1,000 percent increase or decrease. The burning rate of propellants not compacted into solids is impossible to predict; so experience will have to be gained from trial and error methods.

10. SPECIFIC IMPULSE

The most commonly used method to compare the performance of one rocket to that of another rocket is called specific impulse. This is a measure of the amount of thrust created per pound of propellant consumed each second. Specific impulse (I_{sp}) is computed by the following equation. The unit of measure of specific impulse is seconds.

$$I_{sp} = \frac{\text{thrust in pounds}}{\text{pounds burned per second}}$$

The higher the value, the better the propulsion system.

11. PROPELLANT LOADING AND COMPACTION

For a uniform reaction, it is usually necessary that the propellant be uniformly mixed and compacted. Some loose propellants burn so rapidly that an explosion results. The solid propellants must be finely powdered and then mixed thoroughly. A hand-operated, rotating cylinder (properly grounded to prevent a buildup of static electricity) provides fairly good mixing. A number of methods are available to increase the density of a particular grain. Some of these methods are mechanical or hydraulic press, hand tamping, use of a solvent, and vibration. Of these four methods, the press and hand tamping were found to be particularly unsatisfactory for zinc and sulfur. Zinc and sulfur are both soluble in alcohol. A puttylike mixture can be made and packed into the motor chamber with relative ease. If this method is used, a period of several weeks is required to cure the grain, and more burning surface is required than is available with an end burning grain. The fastest and most satisfactory method is that of vibration. This can be accomplished by hand, simply by a vigorous tapping on the outside of the rocket chamber with a plastic hammer. If you have a vibrator-type electric sander, this may be held against the engine wall. If the electric vibrator is used, it is essential that the end of the engine be closed with a plastic bag held in place with a rubber band and that the vibration be conducted in a place where no residual zinc and sulfur dust remains in the air. For consistent results, it is necessary to compact to a known density. First determine the volume of the chamber, and then, using the desired density of the compacted propellant, determine the weight of propellant to add. Compact until that weight fills the chamber. The equations to use in the filling operations are as follows:

Downloaded from http://www.everyspec.com

a. Volume. The volume (Vol) of a cylinder equals the cross sectional area (A) times the length (L).

$$\text{Vol} = AL = \frac{\pi d^2 L}{4} \quad \text{(All dimensions in either inches or feet.)}$$

b. Density. The density of a substance is the weight (w) divided by the volume (Vol).

$$\text{Density} = \frac{\text{weight}}{\text{volume}} = \frac{w}{\text{Vol}}$$

For example, the density of water is 62.4 $\frac{\text{lbs}}{\text{ft}^3}$;

zinc, 440 $\frac{\text{lbs}}{\text{ft}^3}$;

sulfur, 125 $\frac{\text{lbs}}{\text{ft}^3}$.

c. Weight. The weight of propellant to use equals the volume times the density (D).

$$w = \text{Vol} \times D$$

If density is in pounds per cubic foot, the volume must be in cubic feet. To convert cubic inches to cubic feet divide by 1728. If the propellant density is unknown, compact as much as possible into the chamber. Weigh the rocket before and after loading to determine the weight of propellant added. Using the dimensions of the chamber, compute the volume in cubic feet. The density equals the weight divided by the volume. Record this information with the other data about the rocket. If this rocket is a success and you wish to build another rocket with an identical engine, the density could be repeated. Note, however, that the length of the combustion chamber does not affect burning rate or thrust when end burning of a solid grain is used. So in theory you could make the chamber longer or shorter without affecting thrust. Also, it should be noted that there are certain practical limits in combustion chamber length dictated by other considerations. Range is dependent on the amount of propellant used, and the amount of propellant used depends on the length of the combustion chamber.

Downloaded from http://www.everyspec.com

CHAPTER 3

ROCKET ENGINE DESIGN

12. GENERAL

A rocket engine is a device for converting heat energy into kinetic energy. The solid propellants are ignited and burn, producing hot, high pressure gases in the combustion chamber. The function of the nozzle is to convert the random motion of these turbulent gases into a directed motion to the rear of the rocket. The nozzle design has the most critical shape and dimensions of all the rocket parts. The design is based on the DeLaval nozzle (fig 5). The converging section of the nozzle causes the gas velocity to increase until sonic velocity is reached at the throat. The diverging section then acts to further increase the velocity. At the exit, velocities as high as 2, 000 feet per second are easily attained.

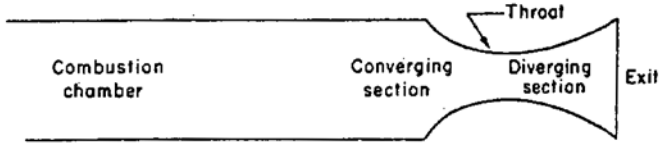


Figure 5. DeLaval nozzle adapted for rocket engine.

13. THRUST

Contrary to popular belief, the rocket does not produce thrust by pushing against the atmosphere. The thrust (F) is obtained principally by increasing the velocity (V) of the gases from a zero value inside the chamber to a high value as the gases leave the exit. This is usually referred to as increasing the momentum of the gases. Momentum (M) is the quantity of motion and is measured by the product of the mass (m) of the object and its velocity. The thrust equation can be developed by the following:

$$\text{Force} = \frac{(\text{momentum at exit} - \text{momentum in chamber})}{\text{time to move from chamber to exit}}$$

$$F = \frac{\text{mass} \times V_{exit} - \text{mass} \times V_{chamber}}{\text{time}}$$

Downloaded from http://www.everyspec.com

$$F = \frac{\frac{w}{g} \times V_e - \frac{W}{g} \times V_c}{t}$$

Where mass = $\frac{w}{g} = \frac{\text{weight}}{\text{gravity}}$

V = velocity

But $V_c = 0$ since the propellant is initially at rest in the chamber.

Therefore $F = \frac{w}{tg} V_e$ where $\frac{w}{t}$ is weight of propellant burned each second and is usually noted w.

The term "V_e" refers to exhaust velocity as well as exit velocity. Either term may be used since both mean the same. The equation may now be written--

$$F = \frac{w}{g} V_e$$

4. EXHAUST VELOCITY

One form of the equation for the theoretical exhaust velocity is--

$$V_e = \sqrt{\frac{2g\gamma}{\gamma - 1} RT_c \left[1 - \left(\frac{P_e}{P_c} \right)^{\frac{\gamma - 1}{\gamma}} \right]}$$

This introduces some terms which seem complex but are not too difficult when discussed separately.

g = gravitational constant = 32.2 ft/sec^2

γ = (gamma) specific heat ratio

R = particular gas constant

T_c = chamber temperature in degrees Rankine (°R)

P_c = chamber pressure in pounds per square inch absolute (psia)

P_e = exit or exhaust pressure in psia

The term "γ" (gamma) refers to the ratio of the specific heats of the propellant. Specific heat is the amount of heat required to raise 1 pound of a substance 1° Fahrenheit. If, during the heating process, the gas is kept at constant pressure the specific heat is referred to as C_p, the specific heat at constant pressure. Likewise, the term C_v is the specific heat at constant volume or the condition where a closed container of gas is heated. The ratio of C_p to C_v is known as γ (gamma), the specific heat ratio. The term "R" is the particular gas constant and is found by dividing the universal gas constant R' by the molecular weight of the propellant:

Downloaded from http://www.everyspec.com

$$R = \frac{R'}{M_w} = \frac{1544}{M_w} \quad \frac{\text{ft-lb}}{\text{mole} \cdot {}^\circ R} \Big/ \text{lb/mole}$$

Molecular weight (or formula weight) is discussed in chapter 2 under propellants and combustion. The average molecular weight of ZnS, the combustion product of our 2.04:1 zinc-sulfur mixture, is 97.45 lb/mole. Thus, for ZnS,

$$R = \frac{1544}{M_w} = \frac{1544}{97.45} = 15.8 \ \frac{\text{ft-lbs}}{\text{lb} \cdot {}^\circ R} = 15.8 \ \text{ft}/{}^\circ R$$

Assuming that 2.04 parts zinc plus 1 part sulfur are used as propellants, the known factors are--

a. Combustion temperature $(T_c) = 3060 \ {}^\circ R$

b. Combustion pressure $(P_c) = 1000$ psia

c. Specific heat ratio $(\gamma) = 1.25$

d. Molecular weight $(M_w) = 97.45$ lb/mole

e. Particular gas constant $(R) = 15.8 \ \text{ft}/{}^\circ R$

f. Exhaust pressure $(P_e) = P_{atmos} = 14.7$ psia

g. Gravitational constant $(g) = 32.2 \ \text{ft/sec}^2$

$$V_{exhaust} = \sqrt{\frac{2g\gamma}{\gamma - 1} RT_c \left[1 - \left(\frac{P_e}{P_c}\right)^{\frac{\gamma - 1}{\gamma}}\right]}$$

$$V_{exhaust} = \sqrt{\frac{2 \times 32.2 \times 1.25}{1.25 - 1} \times 15.8 \times 3060 \times \left[1 - \left(\frac{14.7}{1000}\right)^{\frac{1.25 - 1}{1.25}}\right]}$$

*For values of $\left[1 - \left(\frac{P_e}{P_c}\right)^{\frac{\gamma - 1}{\gamma}}\right]$ see table I.

Downloaded from http://www.everyspec.com

V_e = 2980 ft/sec, the ideal or theoretical exhaust. The effective exhaust velocity or that portion of the exhaust which creates thrust in the forward direction is normally about 90 percent of the calculated velocity. This correction is necessary because of the diverging exhaust and because of losses due to friction. When zinc and sulfur are used as propellants, another factor must be considered. The heat of sublimation of zinc sulfide is approximately 2600° R which means that the exhaust products change from a gas to a solid at this temperature and the exhaust may no longer expand to increase the exhaust velocity. For this reason, a total correction factor of 50 percent of the theoretical exhaust velocity will be applied to obtain an effective exhaust velocity. The effective exhaust velocity (V_{eff}) then becomes:

$$V_{eff} = 0.50 \; V_e = (2980)(0.50) = 1490 \text{ ft/sec}$$

Table I. Expansion Ratio Efficiency Factors.

Values of $\left[1 - \left(\frac{P_e}{P_c} \right)^{\frac{\gamma - 1}{\gamma}} \right]$ Where $P_e = P_{atmos} = 14.7$ psia

Values of γ

P_c (psia)	1.15	1.20	1.25	1.30	1.40
600	0.384	0.460	0.523	0.574	0.655
700	0.396	0.474	0.539	0.590	0.671
800	0.407	0.486	0.551	0.602	0.683
900	0.416	0.495	0.561	0.612	0.693
1000	0.424	0.504	0.570	0.622	0.703
1100	0.431	0.511	0.578	0.630	0.711
1200	0.437	0.518	0.585	0.636	0.718
1300	0.442	0.526	0.591	0.643	0.724
1400	0.448	0.531	0.597	0.650	0.730

15. DESIGN PROBLEM 1

Problem: To design a rocket engine with the following characteristics:

Desired thrust (F) = 800 pounds.

Burning time (t_b) = 0.5 seconds.

Propellant = 2.04 parts zinc, 1 part sulfur.

Downloaded from http://www.everyspec.com

Known factors on propellant performance:

Effective exhaust velocity (V_e) = 1490 feet per second.

Chamber pressure (P_c) = 1000 psia

Chamber temperature (T_c) = 3060° R

Molecular weight (M_w) = 97.45 lbs per mole

Specific heat ratio (γ) = 1.25

Density (D) = 161 lb/ft^3 or 0.0932 lb/in^3

Burning rate (r) = 90 in/sec

a. Propellants. The weight of the propellants (w_p) required can be found by using the thrust equation.

$F = \dot{m} V_e$, where $\dot{m}$ = mass of propellant burned per second

$F = \frac{\dot{w}}{g} V_e$, where $\dot{w}$ = weight of propellant burned per second

$F = \frac{w_p}{t_b g} V_e$, where w_p = total weight of propellant and t_b = burning time

Solving for w_p,

$$w_p = \frac{F t_b g}{V_e} = \frac{800 \text{ lbs} \times 0.5 \text{ sec} \times 32.2 \text{ ft/sec}^2}{1490 \text{ ft/sec}}$$

$w_p = 8.64$ lbs

$$w_{zinc} = \frac{2.04 \text{ parts Zn}}{3.04 \text{ parts total}} \times 8.64 = 5.80 \text{ lbs zinc}$$

$$w_{sulfur} = \frac{1 \text{ part S}}{3.04 \text{ parts total}} \times 8.64 = 2.84 \text{ lbs sulfur}$$

$\dot{w}$ = weight of propellant burned per second and equals

$$\frac{\text{total weight}}{\text{burning time}}$$

$$\dot{w} = \frac{8.64 \text{ lbs total}}{0.5 \text{ sec}} = 17.28 \text{ lbs/sec}$$

Downloaded from http://www.everyspec.com

b. Burning surface. The volume of propellant burned per second (vol prop per sec) equals the burning surface area (S) times the burning rate (r) or

$$\text{Vol prop per sec} = Sr$$

The volume burned per second also equals the weight per second ($\dot{w}$) divided by the density (D) or

$$\text{Vol prop per sec} = \frac{\dot{w}}{D}$$

Equate these two volume equations to find the burning surface S.

$$Sr = \frac{\dot{w}}{D}$$

$$S = \frac{\dot{w}}{rD}$$

$$S = \frac{17.28 \text{ lb/sec}}{90 \text{ in/sec } 0.0932 \text{ lb/in}^3}$$

$$S = 2.06 \text{ in}^2$$

c. Grain size.

Assume end burning $\qquad$ Area = $S = \frac{\pi \text{ diameter}^2}{4}$

Grain diameter = $d = \sqrt{\frac{4S}{\pi}} = \sqrt{\frac{4\ (2.06)}{\pi}} = 1.62$ inches

Grain length = L = burning rate x burning time

$$L = 90 \text{ in/sec} \times 0.5 \text{ sec} = 45 \text{ inches}$$

d. Wall thickness (t_w) of combustion chamber. For short burning times, assume a safety factor of 4 for working stress. This is actually a temperature correction. For example, if low carbon steel (SAE 1020) has an ultimate tensile strength of 62,400 pounds per square inch (psi), use 15,600 psi (62,400 ÷ 4).

$$t_w = \frac{P_c \times \text{radius}}{\text{allowable stress}}$$

$$= \frac{1000 \text{ lbs/in}^2 \times 0.81 \text{ in}}{15,600 \text{ lbs/in}^2}$$

$t_w = 0.0519$ inches required.

Use 16-gauge steel tubing (0.0625 inch wall thickness) with 1 3/4-inch O. D. and 1 5/8-inch I. D.

Downloaded from http://www.everyspec.com

e. Nozzle dimensions.

(1) Throat. The throat diameter can be calculated from a thrust equation which involves a coefficient of force C_F.

$$F = C_F A_t P_c$$

The coefficient C_F can be measured experimentally or can be calculated.

The calculated value of C_F can be taken from table II and for the value of chamber pressure of 1,000 psi and specific heat ratio 1.25, $C_F = 1.57$.

$$A_t = \frac{F}{C_F P_c} = \frac{800}{(1.57)(1000)} = 0.51 \text{ in}^2$$

$$d_t = \sqrt{\frac{4}{\pi} 0.51} = 0.806 \text{ inch}$$

Figure 6 shows three typical nozzle constructions.

(2) Exit area and diameter. To properly expand the gases to atmospheric pressure and, therefore, to the maximum velocity, a particular size nozzle exit is required. From computations much too detailed to discuss here, a relationship between throat and exit areas is given in table III. Using a chamber pressure of 1,000 psi and specific heat ratio of 1.25 for zinc-sulfur, table III yields a value of $\frac{A_e}{A_t} = 8.2$ from which we can determine that

$$A_e = 8.2 A_t$$

A_t has been computed as 0.51 in^2

$$A_e = 8.2 \times 0.51 \text{ in}^2 = 4.18 \text{ in}^2$$

$$d_e = \sqrt{\frac{4}{\pi} A_e} = \sqrt{\frac{4}{\pi} (4.18)} = 2.31 \text{ inches}$$

Downloaded from http://www.everyspec.com

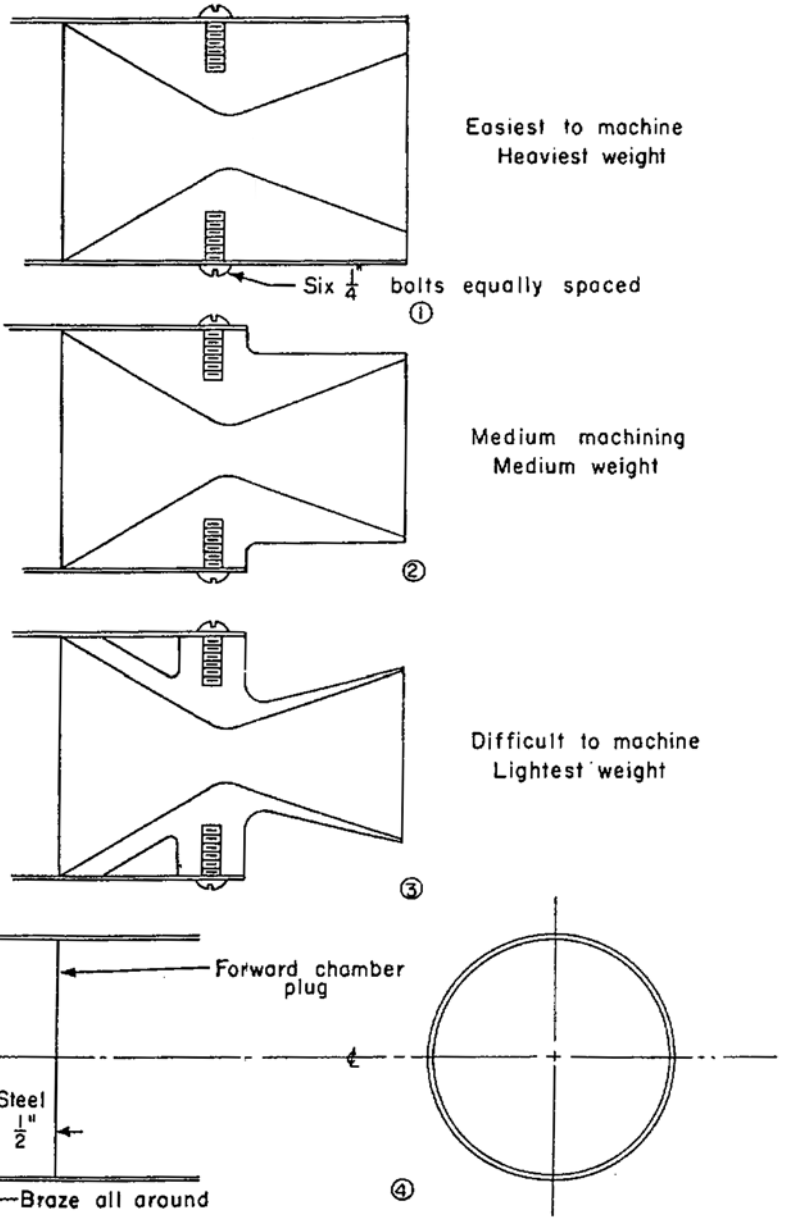


Figure 6. Typical nozzle and plug constructions.

Downloaded from http://www.everyspec.com

Table II. Coefficient of Thrust, C_F where $P_e = P_{atmos} = 14.7$ psia

P_c (psia) \ γ	1.15	1.20	1.25	1.30	1.40
600	1.55	1.52	1.50	1.48	1.46
700	1.58	1.54	1.52	1.50	1.48
800	1.60	1.56	1.54	1.52	1.50
900	1.62	1.58	1.56	1.54	1.51
1000	1.63	1.59	1.57	1.55	1.52
1100	1.64	1.60	1.58	1.56	1.53
1200	1.66	1.62	1.59	1.56	1.54
1300	1.67	1.63	1.60	1.57	1.54
1400	1.68	1.64	1.61	1.58	1.55

Table III. Nozzle Area Expansion Ratio.

Area ratio = $\frac{A_e}{A_t}$ Where $P_e = P_{atmos} = 14.7$ psia

P_c (psia) \ γ	1.15	1.2	1.25	1.3	1.4
600	6.8	6.0	5.6	5.2	4.5
700	7.6	6.8	6.3	5.8	5.0
800	8.4	7.6	6.8	6.4	5.4
900	9.2	8.2	7.4	6.8	5.8
1000	10.0	8.8	8.2	7.4	6.2
1100	10.9	9.5	8.7	7.9	6.7
1200	11.6	10.2	9.3	8.4	7.0
1300	12.4	10.8	9.8	8.9	7.4
1400	13.0	11.5	10.4	9.4	7.7

f. Engine dimensions (fig 7). Use 1 3/4-inch O. D., 1/16-inch thick tubing, 30° converging angle, and 15° diverging angle.

(1) Length of converging section:

$$L_{con} = 1/2 \frac{(d_c - d_t)}{\tan 30°}$$

$$= 1/2 \frac{(1.625 - 0.806)}{0.577}$$

$$L_{con} = 0.71 \text{ in}$$

(2) Length of diverging section:

$$L_{div} = 1/2 \frac{(d_e - d_t)}{\tan 15°}$$

Downloaded from http://www.everyspec.com

$$= \frac{1/2\ (2.31 - 0.806)}{0.268}$$

$$L_{div} = 2.80 \text{ in}$$

Note. Increase the computed lengths slightly to allow rounding of the throat to preserve flow continuity without increasing the throat dimension.

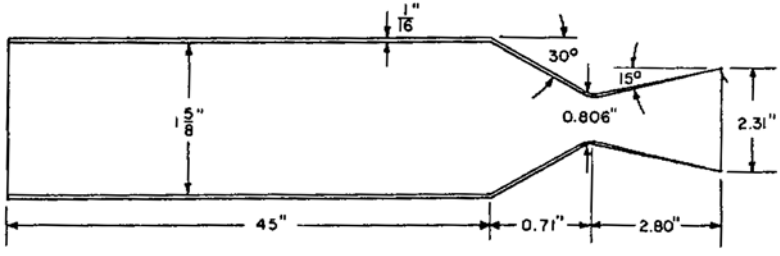


Figure 7. Engine dimension.

16. DESIGN PROBLEM 2

Question: With a given chamber diameter, what are the required nozzle dimensions and the thrust produced? Assume the following piece of tubing is available:

1/16-inch thick
2-inch outside diameter
1 7/8-inch inside diameter
low carbon steel (SAE 1020)
4 feet long

Problem

Design a rocket using zinc and sulfur propellants. The performance factors for Zn + S (previously computed) are as follows:

Use 2.04 parts zinc to 1 part sulfur.

Molecular weight (M_w) = 97.45 lbs per mole.

Combustion temperature (T_c) = 3060° Rankine

Specific heat ratio (γ) = 1.25

Downloaded from http://www.everyspec.com

Combustion pressure (P_c) = 1000 psia

Burning rate (r) = 90 inches per sec

Density (D) = 161 lbs/ft^3 = 0.0932 lb/in^3

Particular gas constant (R) = $\frac{1544}{M} = \frac{1544}{97.45}$ = 15.8 ft/°R

Effective exhaust velocity (V_e) = 1490 ft/sec

Thrust coefficient (C_F) = 1.57

a. Burning surface.

Assume the grain will burn on the end only. The area then becomes $\frac{\pi d^2}{4}$, or $S = \frac{\pi d^2}{4} = \frac{\pi (1.875)^2}{4} = 2.76$ in^2

b. Weight of propellant.

(1) The weight burned each second ($\dot{w}_p$) equals the volume per second times the density. As previously discussed, the volume of propellant burned each second equals the exposed burning area (S) times the burning rate (r).

$\dot{w}_p$ = volume per second x density

$\dot{w}_p = S \times r \times D$

$\dot{w}_p = 2.76$ in$^2 \times 90$ in/sec $\times$ 0.0932 lb/in^3

$\dot{w}_p = 23.15$ lbs per second

(2) The tubing available is 48 inches long. Assume 3 inches are required to mount the nozzle and forward plug. The space available for propellant is 45 inches. The burning time may now be computed by dividing the length (L_c) by the burning rate (r).

$$t_b = \frac{L_c}{r} = \frac{45 \text{in}}{90 \text{ in/sec}} = 0.5 \text{ sec}$$

(3) The total weight of propellant (w_p) equals the weight per second ($\dot{w}_p$) times the burning time (t_b) or,

$w_p = \dot{w}_p \ t_b$

$w_p = 23.15$ lbs x 0.5 sec

Downloaded from http://www.everyspec.com

$w_p = 11.58$ lbs

$$w_{zinc} = \frac{2.04 \text{ parts}}{3.04 \text{ parts total}} = 11.58 \text{ lbs} = 7.77 \text{ lbs}$$

$$w_{sulfur} = \frac{1 \text{ part}}{3.04 \text{ parts total}} = 11.58 \text{ lbs} = 3.81 \text{ lbs}$$

c. Thrust.

Using the basic thrust equation, the thrust can be computed as follows:

$$F = \dot{m} V_e$$

$$F = \frac{\dot{w}}{g} V_e$$

$$F = \frac{23.15}{32.2} \times 1490$$

$$F = 1070 \text{ lbs}$$

d. Throat dimensions.

$$A_t = \frac{F}{C_F P_c} = \frac{1070}{(1.57)(1000)} = 0.682 \text{ in}^2$$

$$d_t = \sqrt{\frac{4}{\pi} A_t} = \sqrt{\frac{4}{\pi} \times 0.682} = 0.932 \text{ in}$$

e. Exit dimensions.

$A_e = 8.2\ A_t$ from area ratio table

$A_e = 8.2\ (0.682) = 5.59 \text{ in}^2$

$$d_e = \sqrt{\frac{4\ A_e}{\pi}} = \sqrt{\frac{4 \times 5.59}{\pi}} = 2.67 \text{ in}$$

f. Chamber and nozzle dimensions (fig 8).

(1) Length of converging section:

$$L_{con} = \frac{\frac{1}{2}(d_c - d_t)}{\tan 30^\circ}$$

$$= \frac{\frac{1}{2}(1.875 - 0.932)}{0.577}$$

$L_{con} = 0.82$ in

Downloaded from http://www.everyspec.com

(2) Length of diverging section:

$$L_{div} = \frac{1}{2}\,\frac{(d_e - d_t)}{\tan 15^\circ}$$

$$= \frac{1}{2}\,\frac{(2.67 - 0.932)}{0.268}$$

$$L_{div} = 3.24 \text{ in}$$

Note. The lengths of the converging and diverging sections are only approximate. Actual lengths should be increased slightly to allow the throat to be rounded, thus preserving flow continuity without increasing the computed throat diameter.

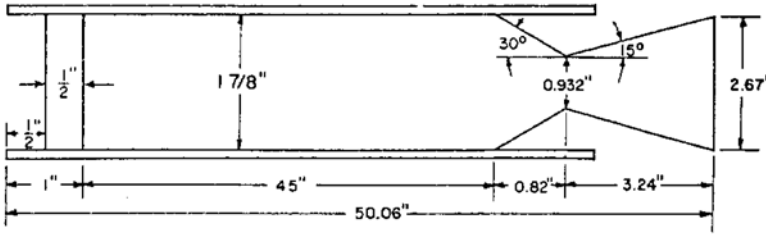


Figure 8. Chamber and nozzle.

Downloaded from http://www.everyspec.com

CHAPTER 4

IGNITION SYSTEMS

17. SYSTEM COMPONENTS

Ignition of a rocket is a very critical operation. Improper ignition can easily cause a rocket to explode. For that reason, no one should be near the rocket during ignition. This means that a remote controlled ignition system is required. Although powder train fuse ignition is possible, it is not recommended because of the uncertainty of its operation and because the chamber must normally be sealed during ignition. A satisfactory ignition system can be easily made by using an electrical system. Electric current is used to heat wires around which loose propellant has been placed. Completing the electric circuit through a battery provides current to heat the loose propellant. The propellant burns, creating pressure and heat which ignites the rest of the propellant. A typical ignition system consists of an igniter inside the chamber, leads to a relay box to which the battery is connected, and a remote firing switch which activates the relay to cause battery power to heat the igniter.

a. Igniter. The igniter can be made from a few turns of high resistance iron or steel wire. The wire resistance must be such that it glows and melts before the lead-in wires melt. The igniter effectively short circuits the battery when the fire switch is operated so that a very high current flows until the igniter melts. A typical igniter is shown in figure 9.

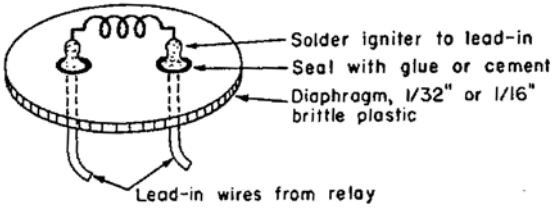


Figure 9. Typical igniter.

b. Relay box. See figure 10. The relay box should provide two features. As its name implies, its primary function is to relay battery power to the igniter at the proper time. Of almost equal importance, however, is the requirement that the relay box should be constructed to provide complete safety for the personnel who attach the igniter leads to the relay box. To assure maximum current and voltage for the igniter, the relay

Downloaded from http://www.everyspec.com

box must be within about 10 feet of the rocket. To prevent accidental ignition, a safety switch should be incorporated into the circuit to short out the igniter circuit and to open the power circuit. If the indicator bulb is on, the circuit is safe to connect. If all other operations are complete and the indicator light is on, the arm-safe switch can be positioned to the unsafe or "arm" position. Then the fire switch can be used to energize the igniter. The capacitor is used to prevent arcing across the terminals of the firing switch when it is turned to the OFF position.

c. Firing panel. The firing panel (fig 10) is used to mount the firing switch and to provide connections for the two wire cables.

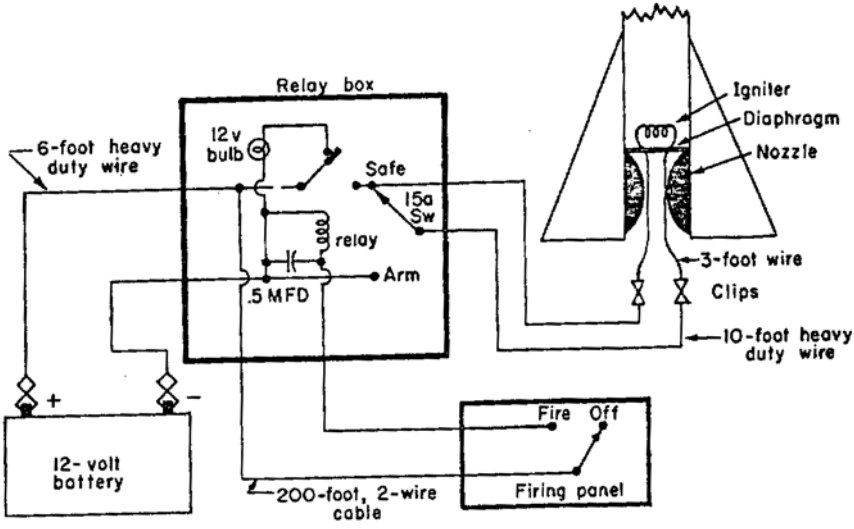


Figure 10. Rocket ignition system.

18. FIRING SEQUENCE

A typical sequence of connecting the electrical circuits and firing the rocket consists of the following steps:

Downloaded from http://www.everyspec.com

a. Check that--

(1) FIRE switch is off.

(2) SAFETY switch is at SAFE.

(3) Rocket igniter wires are wrapped together.

b. Install relay box approximately 10 feet from the launcher.

c. Connect battery to relay box.

d. Check that the relay safety light is on.

e. Connect firing panel to relay box.

f. Test ignition system:

(1) Attach extra igniter to relay box.

(2) Place ARM-SAFE switch to ARM.

(3) Operate FIRE switch.

(4) Igniter burns through.

(5) Turn FIRE switch off.

(6) Place ARM-SAFE switch to SAFE.

g. Attach leads to rocket igniter.

h. Warn all personnel that rocket will be fired. (Everyone should be at least 200 feet from rocket and behind protective cover.)

i. Operate FIRE switch.

j. When rocket ignites, turn FIRE switch off to prevent battery drain.

Downloaded from http://www.everyspec.com

CHAPTER 5

AERODYNAMIC SURFACES

19. GENERAL

Every external part of the rocket will affect the flight. All exposed surfaces cause drag which slows down the rocket. However, some parts are required to help stabilize the rocket and other parts are required to house the engine.

20. NOSE CONE

The nose cone is designed to reduce drag by gradually dividing the air flow around the rocket. Nose cones are generally made at an angle of about 30° and are curved at the base to meet the cylindrical body section. However, the design is not too critical and you may use any angle you desire, but drag increases as the angle increases. Examples of nose cone attachments and shapes are shown in figures 11 ① and ②

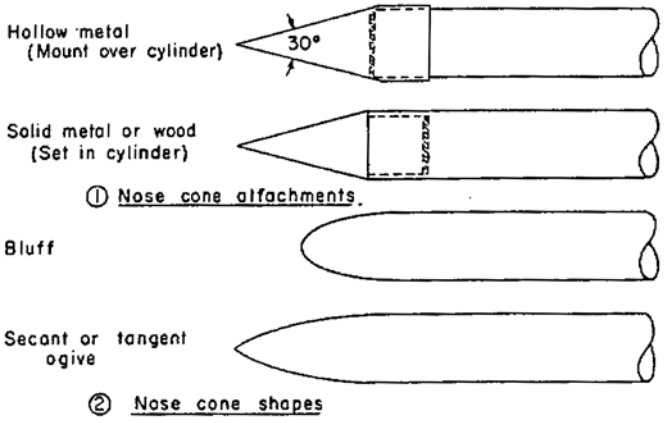


Figure 11. Examples of nose cones.

21. BODY

The rocket body is generally designed as a cylinder. This provides a large internal volume compared to the surface exposed; so less surface materials are required. If the rocket is traveling directly into the wind,

Downloaded from http://www.everyspec.com

the body creates no appreciable drag. However, if the rocket thrust is slightly offset or if the tail surfaces are not properly alined, the body does create drag as it goes through the air at an angle. Making the body cylindrical and eliminating as many external accessories as possible provides the minimum drag. There are two major construction methods used for the body. One method uses the external surface of the engine as the body (fig 12). The nose cone and tail fins are fastened directly to the engine. In effect, the engine and body are the same unit. This is probably the simplest and lightest construction possible.

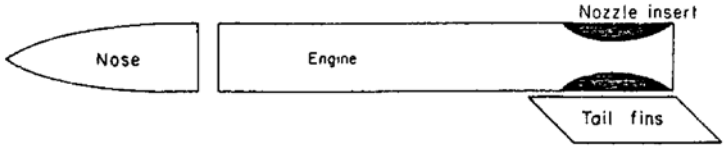


Figure 12. Engine and body as same unit.

The other method requires the construction of a cylindrical body into which the engine is inserted and fastened (fig 13). The nose section and tail fins are also fastened to the body. Light sheet metal can be rolled to form the body.

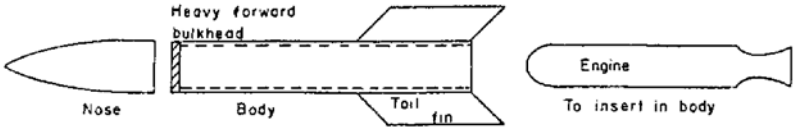


Figure 13. Engine and body as separate units.

22. TAIL FINS

The tail fins are normally made from sheet metal or aluminum. Wood and paper fins cannot withstand the forces normally present when the rocket is operating. From 3 to 6 tail fins can be used. When attached to the rocket, they must be carefully alined in the direction of the center line of the rocket. The fins can be fastened with screws or banded to the

Downloaded from http://www.everyspec.com

body (fig 15). The fins should be bent at a right angle near the base to provide a fastening surface. Normally 1/16-inch steel or 1/8-inch aluminum are suitable for the fins. The total span from the tip of one fin to the tip of another should not exceed 200 times the thickness. Otherwise the fins will bend too easily and may begin vibrating and cause the rocket to break up or tumble. Various designs are shown in figure 14.

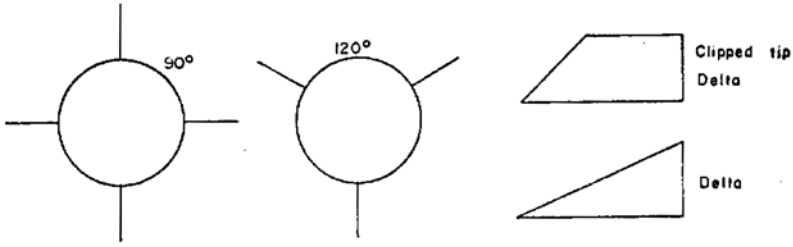
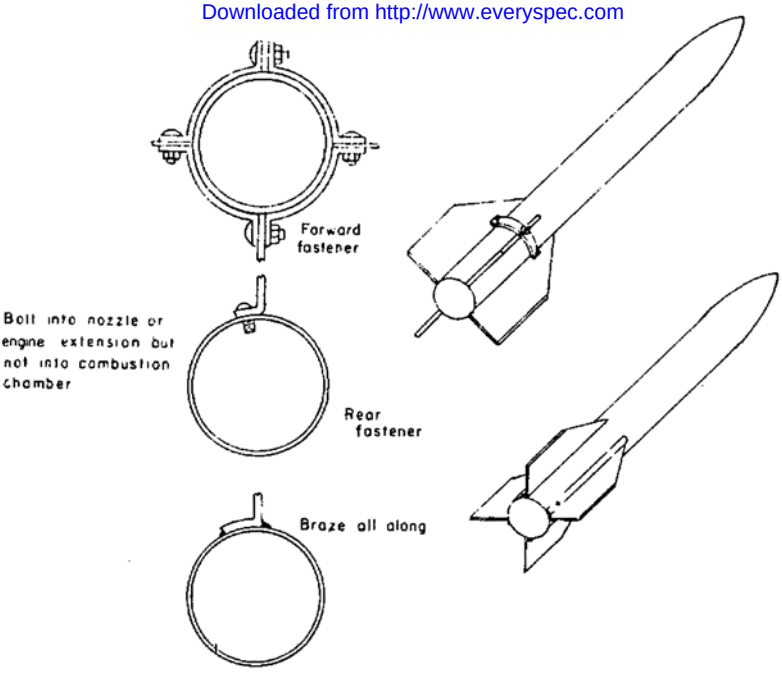
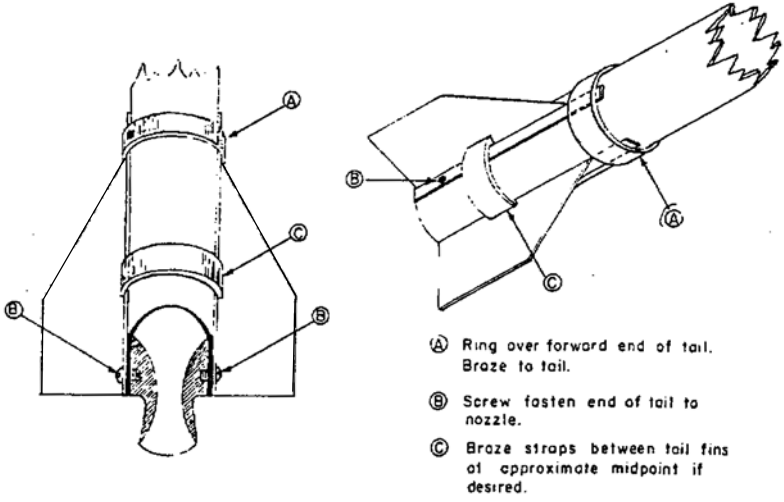


Figure 14. Tail fin designs.

Downloaded from http://www.everyspec.com



① Fin assembly detail


Ⓐ Ring over forward end of tail. Braze to tail.
Ⓑ Screw fasten end of tail to nozzle.
Ⓒ Braze straps between tail fins at approximate midpoint if desired.

② "Strap method" to avoid brazing to chamber or drilling holes except those to mount nozzle.

Figure 15. Fin assembly.

Downloaded from http://www.everyspec.com

CHAPTER 6

ROCKET LAUNCHERS

23. GENERAL

The rocket launcher is a device which supports the rocket and provides initial control by permitting it to move only in the desired direction. The simplest type of launcher is the platform. The platform supports the missile and is constructed so that it may be oriented in azimuth (the horizontal plane). One disadvantage of this type of launcher is that it does not constrain the movement of the missile in a particular direction; so some type of initial guidance control is required within the rocket itself. Since most amateur rockets are not so guided, another type of launcher must be considered. The rail launcher is one which constrains the rocket during travel through a given distance. A 10-foot rail has sufficient length to allow the velocity of the rocket to increase to a point where the air pressure will keep the tail to the rear and the nose forward. The rail launcher may be oriented in both azimuth and elevation (vertical plane). The rocket should be launched at some angle from the vertical so that the rocket will not fall back on the firing position. To attempt an altitude record, the rocket may be fired at an angle of approximately 85° from the horizontal. To establish range or distance, the rocket should be fired at an angle of about 50° from the horizontal.

24. RAIL LAUNCHERS

The launcher should provide adequate support with a minimum of friction. A number of variations of the rail type launcher are discussed in a through c below.

a. Ring-over-pole (fig 16). The ring-over-pole launcher uses two rings mounted on the rocket and slipped down over a smooth steel pole. The pole must be fastened securely in a solid mount or driven deeply into the ground. The pole is inclined 5° from the vertical and should be as strong as possible to reduce bending and whipping as the rocket rises. A 1-inch diameter ring over a 3/4-inch steel pole will usually provide suitable launching for smaller rockets.

b. Clip on rail (fig 17). An adequate launcher can be made using a 1 x 1 x 1/4 inch angle iron over which metal clips slide. The angle iron must be fastened to a piece of 2-inch pipe or other angle or channel iron for rigidity. This launching rail has the advantage of being easily constructed, has reasonably low friction, and is safe to use, since the rail can be reinforced enough to prevent bending when the rocket is in motion.

c. Slotted rail (fig 18). A slotted rail may be constructed by welding together 4 pieces of 3/4 x 3/4 x 1/8 inch angle iron. The standing legs of two of the angles are welded back to back, forming a channel for rigidity.

Downloaded from http://www.everyspec.com

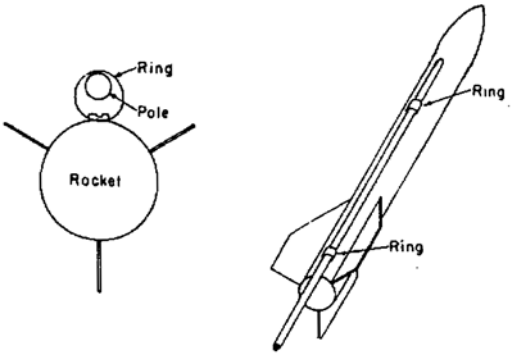


Figure 16. Ring-over-pole.

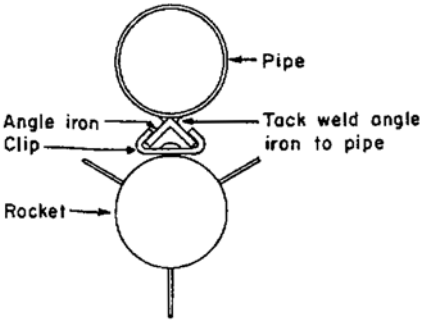


Figure 17. Clip on rail.

The other two pieces of angle iron are welded to the running legs of the angles to form a slotted track. A ready-made version can be made from a 10-foot piece of square steel door track. Two bolts with rounded heads are screwed into the rocket. These hang from inside the track to support the rocket.

d. Launcher base (fig 19). A suitable base may be constructed from a 14-inch square piece of 1/4-inch steel plate. Holes are drilled into each corner of the plate to receive steel holddown stakes. A trunnion bracket is

Downloaded from http://www.everyspec.com

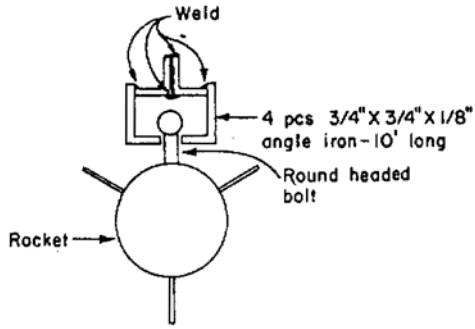


Figure 18. Slotted rail.

welded to the plate, and the rail is fastened to the bracket by means of a bolt. The elevation angle can be adjusted by positioning the adjusting rod in a suitable hole and by taking up the fine adjustment with the turnbuckle. When the launching rail is properly positioned in azimuth and elevation, the guy wires are securely fastened to maintain the direction during the rocket firing operation.

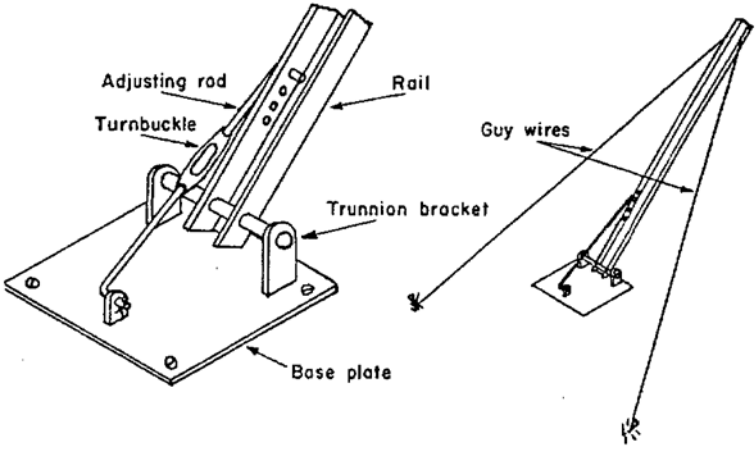


Figure 19. Launcher base.

Downloaded from http://www.everyspec.com

25. ELEVATION QUADRANT (ANGLE ABOVE HORIZONTAL)

Once the rocket launcher has been constructed, the next problem is that of orientation. The launcher may be pointed in the desired direction by means of a compass. The compass is simply set up over the desired launching point, and a stake is set out in the proper compass direction. Set the launcher over the point and sight the rail on the stake marking the direction. A simple elevation quadrant may be constructed by using a protractor and a plumb line or level arm. Place the protractor in position on the launcher rail and raise or lower the rail until the plumb bob or level bubble is in coincidence. The launcher is then at the desired elevation angle.

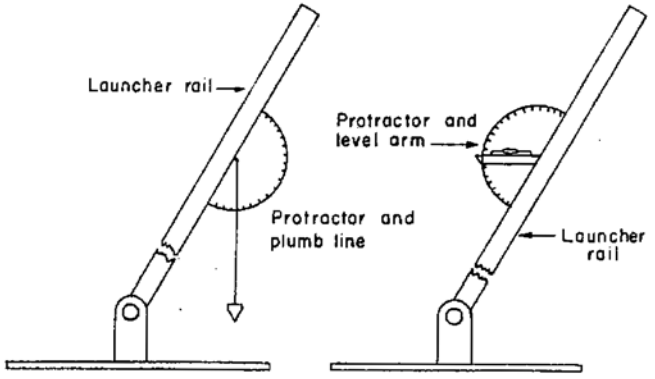


Figure 20. Elevation quadrant.

Downloaded from http://www.everyspec.com

CHAPTER 7

ROCKET TESTING AND PERFORMANCE ANALYSIS

26. GENERAL

The reward for the hours of hard work required to build a rocket is realized a few seconds after the firing switch is operated. A well designed and properly constructed rocket should rise high into the sky and follow an unwavering course. But does height actually present a true picture of the performance of a rocket? And if not, what are the factors which should be considered in evaluating the performance of a rocket and what equipment is available to help analyze performance? One other point which must be considered is that "comparative" performance evaluation is normally used. This means that rockets having similar construction and propellants can be compared to each other to determine which rocket actually used the propellant most efficiently. Then rockets of different construction and using different propellants can be compared to see which propellants and which designs attain the greatest altitude or distance for the least amount of propellant.

27. PRELIMINARY TESTS

Preliminary tests are those which can be performed before the rocket is actually fired into the air. By the use of static firings, firings in which the rocket is held in place, nearly all aspects of rocket design can be tested, and the results can be analyzed before the rocket is actually fired and perhaps lost or so badly damaged at impact that construction or design defects may not be apparent. It could be argued that firing the rocket and determining its altitude or range is proof enough for a rocket design, yet only by chance could a newly organized rocket club anticipate all aspects of rocket design and obtain good results. During the initial work of a new organization or any time a new design is made, a series of tests should be run to determine that each part works properly. Examples of preliminary tests include checking that an ignition circuit will energize the igniter, testing that the igniter will ignite the propellant, and testing that the nozzle diaphragm will hold the flame and pressure long enough to permit good combustion. Then tests can be run to insure that the nozzle and forward plug are securely fastened. Since most amateur rocketeers belong to an organized club, the expenses of preliminary testing could be borne by the club so that the actual cost per individual would be low. For example, developing a suitable ignition system would benefit the entire organization, yet cost each member just a few pennies. Static firing stands can be constructed with very little material. A simple frame to hold a rocket upright would be suitable for firing the rocket when the nose is pointed downward (fig 21). However, for results which more closely approximate the conditions when a rocket is launched, the rocket should be pointed upward so that the jet exhaust is downward. In that case the thrust stand would have to be able to hold down a thrust of up to 1,000

Downloaded from http://www.everyspec.com

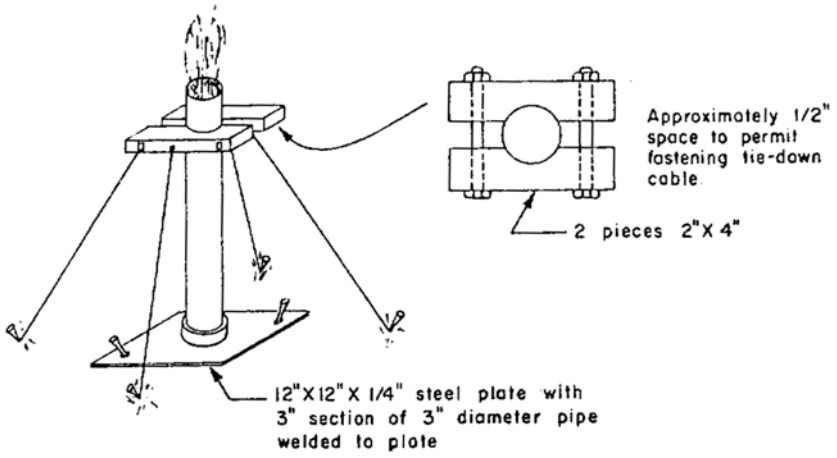

Approximately 1/2" space to permit fastening tie-down cable
2 pieces 2"X 4"
12"X12"X 1/4" steel plate with 3" section of 3" diameter pipe welded to plate

Figure 21. Static test stand A.

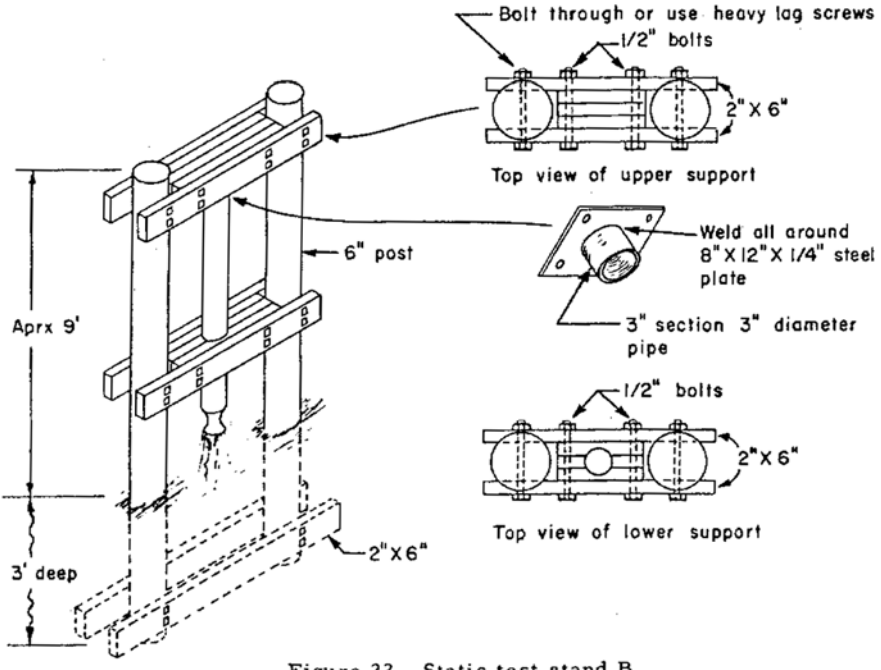


Figure 22. Static test stand B.

Downloaded from http://www.everyspec.com

pounds. A structure anchored to 2 posts sitting about 3 feet deep and about 1 foot apart should be able to withstand 1,000 pounds of thrust (fig 22). Other preliminary tests include those conducted on parachute ejection systems, second stage ignition systems, electronic transmission systems, and smoke ejection systems. The general idea behind all of these tests is to insure the proper operation of as much of the rocket as possible prior to the time the rocket is actually launched. In this manner, considerable money can be saved and better results are obtained, since the rocket can usually be fired again after it has been used to collect information during a static firing.

28. FLIGHT PERFORMANCE EVALUATION

a. General. Although the altitude and range attained in firing are normally considered the most important measures of performance, it is actually altitude or range per pound of propellant which is the better measure of performance. The amount of conversion of chemical energy in the propellant to energy of motion of the rocket actually measures the effectiveness of the propulsion system.

b. Velocity. Although rocket velocity cannot be easily measured directly except by radar, a very simple physical law can be used. It has been observed, by tracking the flight of amateur rockets with radar, that the rocket follows the theoretical ballistic path very closely. For all practical purposes, the rocket is affected only by gravity, and the upward and downward velocities change according to the gravitational attraction. If an object is thrown or fired into the air, it rises for a certain period of time and then falls for the same period. During good weather and when no low clouds are near the firing site, it is possible to measure the flight time of a rocket with a stop watch by observing the rocket until it impacts.

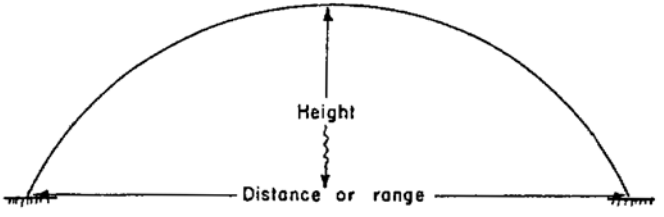


Figure 23. Ballistic path.

Downloaded from http://www.everyspec.com

This time can be called t_f (time of flight). For one-half of this time the rocket rises and then falls for the other half of the time (fig 23). It is easier to discuss what happens to the rocket by considering the time it is falling. At the very top of the trajectory, the rocket ceases upward motion and begins downward motion. For an instant, it has no velocity up or down. Then it begins falling to the earth because of gravitational attraction. Its speed increases 32.2 feet per second every second. At the end of 1 second, it is falling at 32.2 feet per second; at the end of 2 seconds, 64.4 feet per second; at the end of 10 seconds, 322 feet per second; and so on. Its velocity downward equals the acceleration due to gravity times the time, or--

$$V_r = gt, \quad \text{where } g = 32.2 \text{ ft/sec}^2.$$

Therefore, a rocket which has a total time of flight of 40 seconds rises for 20 seconds and falls for 20 seconds. At impact the rocket velocity is--

$$V_r = gt = 32.2 \text{ ft/sec}^2 \times 20 \text{ sec, where } t = \frac{t_f}{2}$$

$$V_r = 644 \text{ ft/sec}$$

For rockets which have a burning time of only 1 or 2 seconds, the velocity at burnout can be assumed to be the velocity at impact. By simply measuring flight time, the burnout velocity can be easily computed and the results are very close to the true velocity as measured by radar.

c. Altitude. To determine the maximum altitude another basic equation is used. The distance an object moves is equal to its average velocity multiplied by the time of motion. An object moving 30 miles per hour for 2 hours travels 60 miles. This rule can be applied to the rocket trajectory. The altitude equals the average velocity multiplied by the time the rocket moves upward. The average velocity ($V_{average}$) is one-half the sum of the velocity (V) at the top and that at the bottom, or--

$$V_{average} = \frac{0 + V_r}{2}$$ since the velocity at the top is zero for an instant and the velocity at impact has been shown to be V_r. The distance up or altitude (H) is--

$$H = V_{average} \times \text{time up}$$

$$H = \frac{V_r}{2} t, \text{ where } t = \frac{t_f}{2}$$

or substituting $V = gt$

$$H = \tfrac{1}{2}gt^2, \text{ where } t = \frac{t_f}{2}$$

Downloaded from http://www.everyspec.com

A rocket with a total time of flight of 40 seconds reaches a maximum altitude:

$$H = \tfrac{1}{2}gt^2 = \tfrac{1}{2} \times 32.2 \text{ ft/sec}^2 \times 20 \text{ sec} \times 20 \text{ sec}$$

$$H = 6,440 \text{ feet}$$

d. Velocity and altitude when fired at low angles. The above discussion is suitable only for nearly vertical firings (above 70° launching angle). For rockets fired at about 50°, where the greatest range is attained, the actual burnout velocity must be obtained by combining 2 velocities, that upward as obtained by the gravity equations and that in range obtained by dividing the range or distance in feet by the time of flight. For example, a rocket fired at approximately 47° goes 13,500 feet and has a time of flight of 30 seconds. What is the maximum altitude and the burnout velocity?

From altitude $H = \tfrac{1}{2}gt^2$, where $t = \frac{t_f}{2}$

$$H = \tfrac{1}{2}(32.2)\left(\frac{30}{2}\right)^2$$

$$H = 3,623 \text{ feet}$$

The vertical velocity (V_v) can be found by--

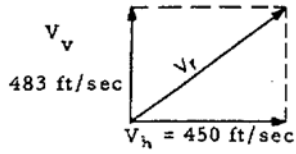
$$V_v = gt, \text{ where } t = \frac{t_f}{2}$$

$$V_v = (32.2)(15) = 483 \text{ ft/sec}$$

The horizontal velocity (V_h) equals the distance divided by time of flight.

$$V_h = \frac{\text{dist}}{\text{time of flight}} = \frac{13,500 \text{ ft}}{30 \text{ sec}} = 450 \text{ ft/sec}$$

The rocket velocity (V_r) is the geometric sum of the two. A solution of a triangle with the velocities represented by the sides may be used.



Downloaded from http://www.everyspec.com

By using the theorem of Pythagoras, the rocket velocity (V_r) may be found.

$$V_r = \sqrt{V_v^2 + V_h^2}$$

$$= \sqrt{(483)^2 + (450)^2}$$

$$= \sqrt{233,300 + 202,500}$$

$$= \sqrt{435,800}$$

$$V_r = 660 \text{ ft/sec}$$

or trigonometrically:

$$V_r = \frac{V_v}{\sin 47^\circ} = \frac{483 \text{ ft/sec}}{0.7314} = 660 \text{ ft/sec}$$

e. Exhaust velocity. The next performance factor which can be computed is exhaust velocity (V_e). It is important that the nozzle operated as intended; that is, it created a supersonic exhaust, which for zinc-sulfur is about 1500 feet per second. The exhaust velocity can be computed from an equation involving the rocket velocity and ratio of total weight to empty weight. The development of this equation is too complex to discuss here but is shown in almost every good rocket propulsion book. The exhaust velocity is designated V_e and is--

$$V_e = \frac{V_r}{\ln \frac{\text{total weight}}{\text{empty weight}}}, \quad \text{Where ln = natural logarithm}$$

If it has been determined that a rocket had a velocity (V_r) of 600 feet per second and weighed 16 pounds total and 8 pounds without propellant then--

$$V_e = \frac{V_r}{\ln \frac{\text{total weight}}{\text{empty weight}}} = \frac{600 \text{ ft/sec}}{\ln \frac{16}{8}} = \frac{600}{0.693} = 866 \text{ ft/sec}$$

This equation provides an average effective exhaust velocity. During the first half of the burning, the rocket exhaust is usually greater than the second half; so at first the exhaust velocity was greater than that computed and then dropped to less than that computed. However, only the average exhaust velocity can be computed.

Downloaded from http://www.everyspec.com

29. THRUST

The next major factor which is computed is thrust. For these computations, one other measurement is required, and that measurement is burning time. Propellant burning time is easily obtained with an ordinary motion picture camera. The camera takes pictures at a certain number of frames per second, usually 16 per second for 8-mm cameras. Use the highest speed on the camera to photograph the rocket during the entire burning period and count the number of frames on which burning is shown. Divide the number counted by the film track speed. For example, if you count 48 frames and took the pictures at 64 frames per second, the burning time equals--

$$t_b = \frac{48 \text{ frames}}{64 \text{ frames/sec}} = 3/4 \text{ second.}$$

The basic thrust equation is--

$$F = \frac{w_p}{t_b g} V_e.$$

If 16.1 pounds of propellant were used, t_b = 0.75 sec, and V_e = 900 ft/sec

$$F = \frac{16.1}{0.75 \times 32.2} \times 900$$

$$F = 600 \text{ pounds.}$$

30. SPECIFIC IMPULSE

The quantity used to determine the effectiveness of a propellant to produce thrust is called specific impulse (I_{sp}) and equals the thrust divided by the weight of propellant burned each second.

$$I_{sp} = \frac{\text{thrust}}{\text{wt}_{prop} \text{ each second}}, \text{ where wt/sec} = \frac{w_p}{t_b}$$

$$I_{sp} = \frac{600}{\frac{16.1}{3/4}}$$

$$I_{sp} = 28 \text{ seconds.}$$

It is desired that I_{sp} be as large as possible. For zinc and sulfur, the I_{sp} is 92 seconds maximum but usually will run about 30 seconds. The efficiency, therefore, is only about 30 percent.

Downloaded from http://www.everyspec.com

CHAPTER 8
ORGANIZATION

31. GENERAL

The material presented in this book has been elementary to a limited area of rocket science; however, it should serve as an indication of the vast scope of the science involved in rocketry. The field of rocketry and space travel is more generally the field of all of the sciences. The ancient Chinese successfully built and fired rockets some 700 years ago. These Chinese established that a vehicle operating on the rocket principle would work. Finding out what this principle was, explaining it, and organizing it into a body of useful information is a comparatively recent development and is, in fact, a main effort in the world today. Legend and historic record, illuminated by present-day organized knowledge, reveal that many individuals throughout the years had great insight to rocketry and were either near the truth or at least headed in that direction.

32. THE SCIENTIFIC METHOD

There are probably many reasons for the great disparity of time between the question and the answer, but lack of communication and organization certainly contributed materially. The curious ones of past ages virtually worked on intellectual islands and the greatest barriers to the solution of their problem was the lack of information of previous experiments. In modern times we have learned to resolve our problems by a method of systematic investigation known as the scientific method. In the scientific method of studying a problem, the problem is divided into small segments. A particular part of the problem is studied by an expert in that field. His contribution of a solution is not necessarily the final answer, for many others have been studying the various aspects of the problem and have been arriving at preliminary solutions. Now comes the big problem. Will the sum of the parts equal the whole? Will the individual solutions now lead to the final desired result? This is where organization comes into the field. All of the preliminary solutions are weighed carefully by an organized group and their effects on each other are measured. The individual solutions are altered as necessary to have a final result which integrates the minor phases of the problem, and the final result is measured against the goal initially set. After a careful study of individual details and an analysis of the relationship between parts, a solution for all aspects of the problem is obtained. So in the study of a major problem, such as a rocket system, the rocket system is divided into as many separate parts as possible. Various methods or solutions for each part are obtained. Combinations of these solutions are then studied as a group where the relationship between parts becomes more apparent. Notes or records of the studies are made so that the problem can be considered carefully. The final rocket is the result of many small contributions from people who learned

Downloaded from http://www.everyspec.com

as much as they could about a particular problem. One person cannot become expert in all aspects of the system but he can learn quite a lot about one problem; so the combination of individuals and their group thinking will lead to good results, results where everyone can feel he made a contribution.

33. ORGANIZE TO LEARN

The real value of your curiosity and interest in the field of rocketry is that of motivation to learn basic scientific principles and to become familiar with the scientific method of dealing with a problem. The best way to accomplish this is to organize into a society or club, under the sponsorship of your school and teachers. Your organization should include a principal sponsor and advisers in the fields of mathematics, physics, and chemistry. In addition to these faculty members, it is desirable to have as many professional advisers as possible from such fields as engineering, physics, chemistry, metallurgy, and electronics, to name but a few.

34. FINANCIAL CONSIDERATIONS

Another consideration in favor of organization is one of finance. A single rocket 2 inches in diameter and 4 feet long will cost about $35 loaded and ready to fire. The associated launching, propellant mixing, and ignition equipment will cost an additional 30 or 40 dollars. This means that an individual undertaking such a project would have a minimum outlay of 65 to 75 dollars, a sum well beyond the means of most school students. Much of the equipment, such as the ignition system and launcher, can be made standard or common equipment and can be used many times. Finally, test equipment, such as stop watches, movie cameras, test stands, and other measuring devices needed to evaluate and give purpose to your work, will very likely not be available to you on any other basis than through an organized club or society. Organization is your first step.

Downloaded from http://www.everyspec.com

CHAPTER 9

SAFETY

35. GENERAL

It has been the policy in the preparation of this booklet to include general precautionary notes throughout the text. Since the keynote and principal motivating factor in its preparation is that of safety, it is appropriate that the specific hazards and precautionary measures be restated for emphasis. Remember, this may be a life or death matter tc the amateur rocketeer, to his neighbors, and to the program itself. Specific areas of danger that will be discussed are legal pitfalls, unqualified advisers, unknown propellants, and rocket firing operations.

36. LEGAL

Most states and many municipalities have enacted legislation banning the manufacture, sale, and firing of fireworks by unlicensed persons. Rockets and rocket fuel are similar to fireworks in many respects; so it is important that you secure an interpretation of your local laws so that your activities can be conducted on a legal basis. When rockets are transported on state highways, they must be handled in accordance with state laws and those governing interstate commerce. It is best to consult the state highway patrol for additional information. When loaded rockets are transported on a military reservation, the igniter must be packaged separately. The transporting vehicle must be clearly marked EXPLOSIVES on the front, rear, and sides. Each vehicle must be equipped with two fire extinguishers. A possibility of legal complication may be encountered because your rocket presents a hazard to air navigation. The rocket must be fired into airspace from which aircraft are restricted, or clearance must be obtained from the Civil Aeronautics Authority. In any event, airspace is regulated and cannot be used indiscriminately. A final and most important legal consideration is that of liability. Before entering into any type of amateur rocket activity, group or individual, it is advisable to secure expert legal guidance concerning your responsibilities. Property damage, injury or death to stock, or injury to an uninvited spectator, while trespassing on your private firing range, could result in costly and unpleasant court action.

37. UNQUALIFIED ADVISERS

A number of the injuries and fatalities resulting from amateur experimentation with fuels and rockets can be attributed directly to unqualified supervisors. Few chemists, physicists, engineers, teachers, or others are qualified to supervise a rocket project in its entirety. Handling of propellants and firing of rockets require a very specialized knowledge and training. The only people qualified to supervise this aspect of a

Downloaded from http://www.everyspec.com

rocket program are those civilian and military people engaged professionally in such activities.

38. UNKNOWN PROPELLANTS

a. The discussion of propellants in this booklet has been deliberately limited to the micrograin propellants and, in this area, specifically to zinc and sulfur. The following rules are to be applied in the case of zinc and sulfur and are generally applicable to all explosive substances:

(1) Handle and mix only under direct expert supervision.

(2) Ground all equipment used in mixing, loading, or handling of mixed propellants to guard against static electrical discharge.

(3) Allow no open flames or sparks.

(4) Do not heat or cook.

(5) Do not grind or subject to compression or shock.

(6) Mix in the open air.

(7) Do not allow excessive micrograin dust to accumulate in the air.

(8) Allow only the minimum essential people near propellant mixing and loading operations or near a loaded rocket.

(9) Handle as small a quantity of propellant as possible.

(10) Mix the propellants near launching site.

(11) Do not load until ready to fire.

(12) Wear flame resistant protective clothing.

(13) Have fire-fighting, rescue, and first-aid equipment standing by during all propellant handling operations.

b. You are specifically advised that most other propellants are too dangerous to be handled by amateurs with amateur equipment, and you are enjoined not to consider them for your rocket project.

(1) Chlorates and perchlorates should not be used by amateurs. The most readily available chlorates, sodium chlorate and potassium chlorate, explode so easily when rubbed, ground, or mixed that they are not even used in military or scientific rockets.

Downloaded from http://www.everyspec.com

(2) Powdered metals, such as iron, magnesium, nickel, and aluminum, can produce an explosive mixture with air when poured from one container to another or when shaken. The dust of some of these metals can ignite spontaneously when floating in air. When these metals are mixed with an oxidizer, they become sensitive to shock.

(3) Nitroglycerine will detonate violently on slight shock and is also sensitive to heat.

(4) Nitrocellulose can also explode when subjected to heat or shock and burns easily in the open air when ignited.

(5) Metallic sodium, metallic potassium, and yellow phosphorus all ignite spontaneously when exposed to air.

(6) Liquid propellants generally present additional hazards, such as poisonous fumes, extreme corrosion, and spontaneous ignition.

39. ROCKET FIRING OPERATIONS

Firing of rockets should be confined to approved firing ranges and conducted under the supervision of qualified individuals. Firing procedures should be thought out and documented in advance of the firing, checked for safety by the experts, and then carefully followed. The ignition system should not be connected until just prior to firing. There should be a means of igniting the rocket electrically from a remote position. Firing leads should not be connected to the electrical source until it is desired to ignite the rocket. All persons participating should be inside suitable bunkers with overhead cover when the rocket is fired. The rocket should never be launched vertically or during a strong wind. The vertically fired rocket endangers the launching site and winds may send it off on a completely unpredicted heading. In the event of a misfire, make three attempts to fire. Then if the propellant does not ignite, wait 30 minutes before approaching the rocket. After a successful firing everyone should remain under cover until it is certain that the rocket has impacted.

40. SUMMARY

Remember that the rocket hobby can be a life and death matter. Select a recommended safe propellant only. Design your rocket with utmost care so that it will perform as expected. Static test the rocket, when possible, prior to firing, observing the same precautions as when firing. Then assemble the rocket, load the propellants, and connect the igniter at the launching site. Expose a minimum number of personnel to the loaded and armed rocket. It is only with extreme caution and great care that you can expect to have a successful and safe firing. Make your rocket project a gratifying experience, not a tragedy.

Downloaded from http://www.everyspec.com

GLOSSARY

TERMS, ABBREVIATIONS, AND DEFINITIONS

A (Area)--The surface extent of any figure, usually in square inches when part of an equation. To convert square feet to square inches multiply by 144.

$$\text{Area of circle} = \frac{\pi \times \text{diameter squared}}{4}.$$

A_e (Exit area)--The cross-sectional area of the rocket engine nozzle where the exhaust gases are released into the atmosphere.

A_t (Throat area)--The cross-sectional area of the nozzle at its smallest inner diameter.

Acceleration--The rate of increase in velocity; for example, increasing velocity from 20 to 50 feet per second in 1 second is an acceleration of 30 feet per second per second.

Aerodynamics--The science concerned with the motion of air and other gases and the forces created.

Airfoil--Any surface designed to obtain a reaction from the atmosphere when in motion.

Ballistic--A type of trajectory described by the motion of any rocket, projectile, or other free-falling object after the propelling force has been removed and which results from the gravitational attraction.

Burnout--The time at which combustion in a rocket engine ceases.

C_F (Thrust coefficient)--Can be calculated or measured from results obtained in static thrust stands.

$$C_F = \frac{F}{p_c A_t} \qquad \text{(measured)}$$

$$C_F = \sqrt{\frac{2\gamma^2}{\gamma - 1}\left(\frac{2}{\gamma+1}\right)^{\frac{\gamma+1}{\gamma-1}}\left[1 - \left(\frac{p_e}{p_c}\right)^{\frac{\gamma-1}{\gamma}}\right]} + \frac{p_e - p_a}{p_c}\,\frac{A_e}{A_t}$$

Note. Values of this equation for various specific heat ratios and chamber pressures are given in table II.

CG (Center of gravity)--The central point in a rocket or other body at which all its weight appears to be concentrated. Suspension of a body at its center of gravity results in perfect balancing.

Downloaded from http://www.everyspec.com

C_p (Specific heat at constant pressure in British thermal units (Btu))--The amount of heat required to raise 1 pound of a substance 1° Fahrenheit while maintaining a constant pressure.

C_v (Specific heat at constant volume in British thermal units (Btu))--The amount of heat required to raise 1 pound of a substance 1° Fahrenheit while maintaining a constant volume.

d--Diameter (inches).

D (Density)--The weight of a substance per unit volume (pounds per cubic foot).

D (Drag)--The aerodynamic force (in pounds) retarding the motion of an object through the atmosphere.

F (Thrust)--The propulsive force (in pounds) created by a jet engine.

$$F = \dot{m} V_e = \frac{w_p}{g t_b} V_e \quad \text{for rockets}$$

$$F = C_F P_c A_t$$

Fin--A fixed or adjustable airfoil attached to the body of a rocket for the purpose of flight control or stability.

g--The acceleration due to gravity (32.2 feet per second per second).

γ (Gamma)--Ratio of specific heats.

I (Impulse)--The product of a force (in pounds) times the duration (in seconds) of that force. I = force x time

I_{sp} (Specific impulse)--The ratio of the thrust produced by the weight of propellant consumed per second. A measure (in seconds) of the effectiveness of a propellant to produce thrust. It is desired that specific impulse be as high as possible.

λ (Lambda)--Mass ratio, total weight of rocket divided by weight without propellant.

Igniter--A device used to initiate propellant burning in a rocket engine combustion chamber.

L--Length (inches or feet).

L_c--Length of combustion chamber (inches).

Downloaded from http://www.everyspec.com

Launcher--A device which supports and positions a rocket to permit movement in a desired direction during takeoff.

Lift--The aerodynamic force on a body measured perpendicular to the direction of motion. Lift is used to turn, stabilize, or support a rocket depending on the location, shape, and angle of a surface with respect to the rocket body.

m (Mass)--A measure of the quantity of matter in an object.

$$m = \frac{\text{weight}}{\text{gravitational constant}} = \frac{w\ (\text{lbs})}{g\ (\text{ft/sec}^2)}$$

The unit of mass is sometimes called a "slug."

$\dot{m}$ (Mass flow rate)--Propellant consumption rate in slugs per second.

M (Momentum)--A quantity of motion measured by the product of the mass of an object times its velocity.

$$M = mV$$

M_v (Mach number)--The ratio of the speed of an object to the local speed of sound.

$$M_v = \frac{\text{speed of object}}{\text{speed of sound}}$$

M_w (Molecular weight)--The total of the atomic weights of the component atoms of a molecule, expressed in pounds per mole.

Nozzle--A channel with changing cross section in which a gas velocity is increased. The DeLaval nozzle consists of a converging and a diverging section which increases the gas velocity to a supersonic value.

Oxidizer--Any substance which reacts with another substance to support burning.

P (Pressure)--The result of the impact of molecules on their surroundings, measured as a force per unit area such as pounds per square inch absolute (psia) or pounds per square inch gage (psig).

Payload--The equipment carried by the rocket which performs no function in relation to the flight such as a smoke flare or transmitter.

R--Gas constant for a particular gas, ft/$^{\circ}$R.

$$R = \frac{R\ \text{universal}}{\text{molecular weight of gas}} = \frac{1544}{M_w}$$

Downloaded from http://www.everyspec.com

S (Surface area)--Square feet or square inches.

Sonic--The speed of sound; the rate at which a pressure disturbance passes through a medium. In the atmosphere the speed of sound equals

$$V_{sound} = 49.1 \sqrt{\text{Temp in deg Rankine}}$$

In any gas the speed of sound equals

$$V_{sound} = \sqrt{\gamma g R T}$$

T--Temperature, usually in degrees Rankine when part of an equation. The temperature in degrees Rankine equals the temperature in degrees Fahrenheit $+459^{o}$.

Vol--Volume (cubic feet or cubic inches).

Volume of cylinder = length x cross-sectional area.

V--Velocity (feet per second).

w--Weight.

w_p--Weight of propellant.

$\dot{w}$--Propellant consumption rate in pounds per second.

SUBSCRIPTS

atmos--Air or atmosphere, such as P_{atmos} (atmospheric pressure).

c--Chamber, such as A_c (cross-sectional area of chamber).

e--Exit or exhaust, such as T_e (temperature of exhaust).

F--Thrust, the propulsive force created by a jet engine, such as C_F (thrust coefficient).

t--Throat, such as V_t (velocity at throat).

L 3635 ARMY-FT. SILL, OKLA.

Downloaded from http://www.everyspec.com

Downloaded from http://www.everyspec.com

Preparing to Fire

The Army Assists